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Prediction of Re-entry Vibration

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AEROSPACE CORPORATION

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by

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San Bernardino Operations
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Approved

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ABSTRACT

The current techniques for establishing vibration criteria are predicated on the scaling of measured flight data. Measured vibrations are scaled by the influencing factors of acoustic sound pressure levels, surface weight and mass loading. The level of confidence in the predicted environment is, therefore, dependent on the applicability of the measured data, e.g., engine and structural similarity, mass loading and mission profile characteristics. To date, flight vibration measurements taken within re-entry vehicles during the re-entry period are practically nonexistent. Of the data available, a considerable portion was transmitted on low frequency telemetry channels (less than 1000 cps) and therefore has very limited usefulness. Thus, to establish re-entry vibration criteria, launch data measured near the payload interface were extrapolated to the aerodynamic re-entry conditions.

The underlying problem in the prediction of re-entry vibrations is the fundamental question regarding the effectiveness of the boundary layer noise to produce structural vibrations, particularly during flight at velocities up to Mach 20. Although the pressure fluctuations in the boundary layer are thought to be larger during the re-entry period than boost, this effect is cancelled, in part, by the increased velocities which distributes the energy over a much broader frequency bandwidth (up to 100 kc). Thus, for the frequency range of interest (up to 2000 cps), the predicted vibration criteria may vary by as much as ten decibels between any two analysts, depending upon how these factors are treated.

This paper presents, in non-dimensional form, recent broadband vibration data which indicates a trend toward higher vibration levels during the re-entry period as compared to the boost period. The data are as yet insufficient both in quantity and quality to accurately assess the effect on vibration levels of all flight parameters (such as effects due to various ablative materials); however cursory checks of these data show that they tend to follow the dynamic pressure characteristics.

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FIGURES

SECTION 1
INTRODUCTION

This paper presents, in a nondimensional form, re-entry vibration data measured on a high ballistic coefficient re-entry vehicle (see Figure 1). The data are presented in non-dimensional form to enable declassification and thereby inform a larger audience of its existence; the actual data are contained in Reference 1 and can be obtained through appropriate security channels.

The prime objective of the measurement program was to assess the vibration magnitude during the re-entry period of flight. The data presented were obtained on a single flight and as such are insufficient to accurately assess the effect of all flight parameters which would be of interest for vibration prediction purposes. Additional data are required to evaluate the numerous configurational effects, such as various ablative materials, velocity and pressure interactions and ballistic coefficients. However, the analyses of these data does indicate that the vibration magnitudes are proportional to vehicle body pressure.

The re-entry vibration levels were compared with other liftoff vibration measurements to form a basis for evaluating the severity of the aerodynamic induced vibrations with plane wave acoustic induced vibrations. This comparison was desirable since there have been diverse opinions among analysts regarding the effectiveness of boundary layer noise in inducing structural vibrations, particularly at velocities of up to Mach 20. The results of wind tunnel tests (Ref. 2 through 5) up to Mach 5 have indicated that overall pressure fluctuations in the boundary layer increases with increasing velocity, and that the boundary layer energy is distributed over a much broader frequency bandwidth. Consequently, although there is an overall increase in pressure, the effect on vibrations in the 0 to 2 kc frequency range (the range of interest) have not been evaluated. In addition, there are no comparisons of vibration data resulting from boundary layer pressures and plane wave pressures which evaluate the correlation of the two types of forcing functions. In other words, assuming a similar spectrum shape for the same frequency bandwidth, will 140 db of boundary layer pressure yield the same response as 140 db of plane wave acoustics? This paper provides a preliminary assessment of this question.

SECTION 2

DESCRIPTION OF THE EXPERIMENT

The re-entry vehicle had initially been instrumented with two piezoelectric accelerometers located on the forward and aft cone shell surface to detect the aerodynamic transition event. These measurements also provided lift-off and boost max q vibration data. However, the vibrations at these locations were not expected to result in the maximum re-entry vibration levels due to the high surface weight of the cone (17.5 lbs/ft^2). In addition, the measurements were of limited interest during re-entry in that they were not located adjacent to component mountings. As a result, the location selected for the re-entry vibration and acoustic measurements was in the aft spherical section of the re-entry vehicle as shown in Figures 2 and 3.

The vibration transducer was mounted adjacent to components weighing approximately 10 pounds on the aft shell structure which had a surface weight of approximately 6 lbs/ft^2. The accelerometer was oriented to sense motion perpendicular to the surface. Since the transition measurements were required to meet the primary flight objectives, a mechanism was activated at 50,000 feet to switch from the transition measurements to the desired re-entry measurement locations. This was considered acceptable since predicted external sound pressure levels were only significant at altitudes below 50,000 feet.

The thermal problems attendant with measuring re-entry boundary layer pressure fluctuations precluded direct external measurement. Therefore, since the boundary layer phenomena could not be measured directly, the internal pressure fluctuations were measured and the effective plane wave external pressure levels were inferred. This is not to imply that the boundary layer noise can be defined by simple plane wave acoustics; however, the inferred levels can be used as effective plane wave acoustics and used in standard prediction scaling techniques. In order to infer the effective external sound pressure level, it was necessary to evaluate the transmission loss through the aft spherical structure. As shown in Figure 4, a ground test was conducted on an aft spherical section which simulated the flight article. The pressure attenuation as a function of frequency was evaluated and is shown in Figure 5.

In addition, since the vehicle was not sealed, it was necessary to measure internal ambient pressure during flight in order to analytically correct for internal and external pressure differences.

SECTION 3

INSTRUMENTATION

The transition vibration measurements were taken during the time period just prior to the Atlas booster ignition and were continuously transmitted until the re-entry vehicle reached a re-entry altitude of 50,000 feet. These two measurements were transmitted on FM/FM IRIG channels 17 and 18. During the time period from 50,000 feet to impact, channel 17 carried the re-entry vibration measurement and channel 18 carried the re-entry acoustic measurement.

Both the transition and re-entry vibration measurements were obtained with piezoelectric accelerometers. The response characteristics of the transducer/amplifier combination was essentially flat from 13 cps to above 2 kc.

The acoustic instrumentation consisted of a matched microphone/amplifier set which was calibrated over the frequency range 50 to 1500 cps. The microphone selected contained a vibration compensating system which effectively eliminated vibration induced responses. A filter within the amplifier attenuated the response above 1500 cps to prevent cross talk and high frequency saturation of the FM channel.

SECTION 4
FLIGHT DATA

VIBRATION DATA

Shown in Figure 6 are envelopes of the normalized acceleration spectral densities for the lift-off, boost maximum dynamic pressure and the re-entry periods. These envelopes are indicative of relative magnitudes, all having been normalized to the same surface weight. The proportionality used in the normalizing process was one of constant force, i.e., $g_{1\ rms} \cdot \text{weight}_1 = g_{2\ rms} \cdot \text{weight}_2$. As can be seen, the envelope shape changes in traversing from the lift-off period to the maximum dynamic pressure period with the primary response shifting from below 600 cps to above 1000 cps. However, no appreciable change in the envelope shape is apparent between the boost maximum dynamic pressure period and the re-entry period although the magnitude of vibration increases significantly during the re-entry period. It is of interest that the vehicle velocity during the boost maximum dynamic pressure period is about 1600 feet per second and is in excess of 16,000 feet per second during the re-entry period. It can be seen that a single envelope covering all conditions would be governed below 600 cps by the lift-off period and above 600 cps by the re-entry period.

A comparison of the free-stream dynamic pressure and the vibration response is shown in Figure 7. These data are presented as nondimensional parameters and were determined by dividing the computed dynamic pressures and the measured vibration by their respective maximum values. Although the general trend of the two parameters is similar (both having approximately the same slope) it is noted that the rate of increase in the magnitude of vibration lags the free-stream dynamic pressure by as much as 18 percent.

A comparison of the measured vehicle base pressure and vibration response is shown in Figure 8. These data are also nondimensionalized by dividing the measured values by the maximum values experienced. The excellent agreement between these two parameters indicates nearly a one to one correspondence between the vehicle base pressure and the induced vibration. It appears logical, therefore, that the effective external sound pressure levels are also increasing proportionally, since the pressure fluctuations are the prime forcing function inducing the vibration.

ACOUSTIC DATA

As previously mentioned, the purpose of the acoustic measurement was to infer an external pressure spectra by measuring the internal pressure levels and correcting for both transmission loss through the structure and for the lower internal pressure conditions. Unfortunately, much of the measured data appear to be system background noise indicating the initial estimates of external levels were too high. However, valid data were obtained for a short time duration which permitted the evaluation of the ratio of fluctuating pressure to base pressure. The ratio of fluctuating root mean square pressure ($\overline{Prms}$) to measured base pressure (P base) was found to be 0.0315. This was somewhat higher than anticipated. It is stressed that the fluctuating pressure covers only the frequency range up to 1500 cps, and consequently this ratio would be even higher if the entire spectrum is considered.

The inferred external pressure spectral density is shown in Figure 9. Note that the maximum value occurs below 200 cps. This fact is somewhat surprising since the majority of the vibration response occurs in the frequency range above 1000 cps. However, similarly shaped boundary layer noise spectra have been measured on a near-conical model during wind tunnel tests. (Reference 6) These spectra were measured at velocities ranging from Mach 1.75 to 5.0 and are reproduced (from Reference 6) in Figure 10. Plotted on Figure 11 are the values measured during the re-entry vehicle experiment in addition to the data of Reference 6. Note that the two sets of normalized data do not fit well. However, they do have similar characteristic shapes which tends to support the method of inferring an external spectra by extrapolating the measured internal spectra.

As was previously mentioned, the external sound pressure levels appear to increase proportionally with increasing base pressure since the vibration/base pressure levels increase with a one to one correspondence. Further, since the vibration envelopes for the re-entry and boost maximum dynamic pressure periods are similar, an attempt to infer the overall sound pressure levels for the boost maximum dynamic pressure period was made. This was done by extrapolating the inferred re-entry sound pressure levels to the dynamic pressure conditions experienced during the boost period on a Titan II vehicle. After correcting for dynamic pressure differences between the Atlas and Titan II trajectories, the inferred value was found to be within 1.5 db of the levels measured near a similar payload shape on a Titan II vehicle (Reference 7).

This is considered to be excellent agreement; however, due to the various extrapolations required and the fact that only one re-entry measurement is now available, the agreement may be coincidental.

SECTION 5

CONCLUSIONS

1. The low frequency boundary layer noise is not as efficient a forcing function as plane wave acoustics. This is apparent since the low frequency vibration response is governed by the lift-off period and the high frequency response is governed by re-entry even though the boundary layer noise spectra below 200 cps is greater than the plane wave acoustics during the lift-off period.

2. The maximum overall rms vibrations occur during the re-entry period and indicate a one to one correspondence with the vehicle base pressure.

3. Assuming the same surface weight throughout the vehicle, the shape of a single envelope covering all periods of flight would be dictated by the lift-off period below 600 cps and by the re-entry period above 600 cps for this configuration.

SECTION 6

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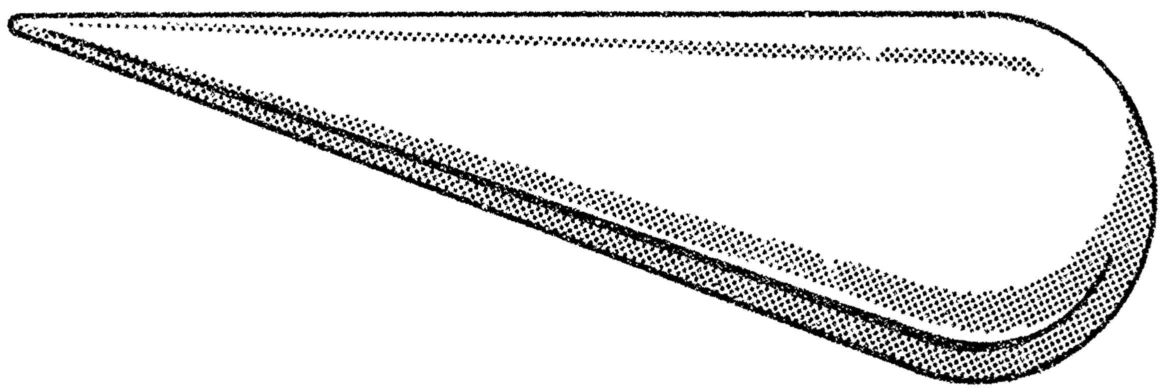

Figure 1. Typical High Ballistic Coefficient Re-entry Vehicle

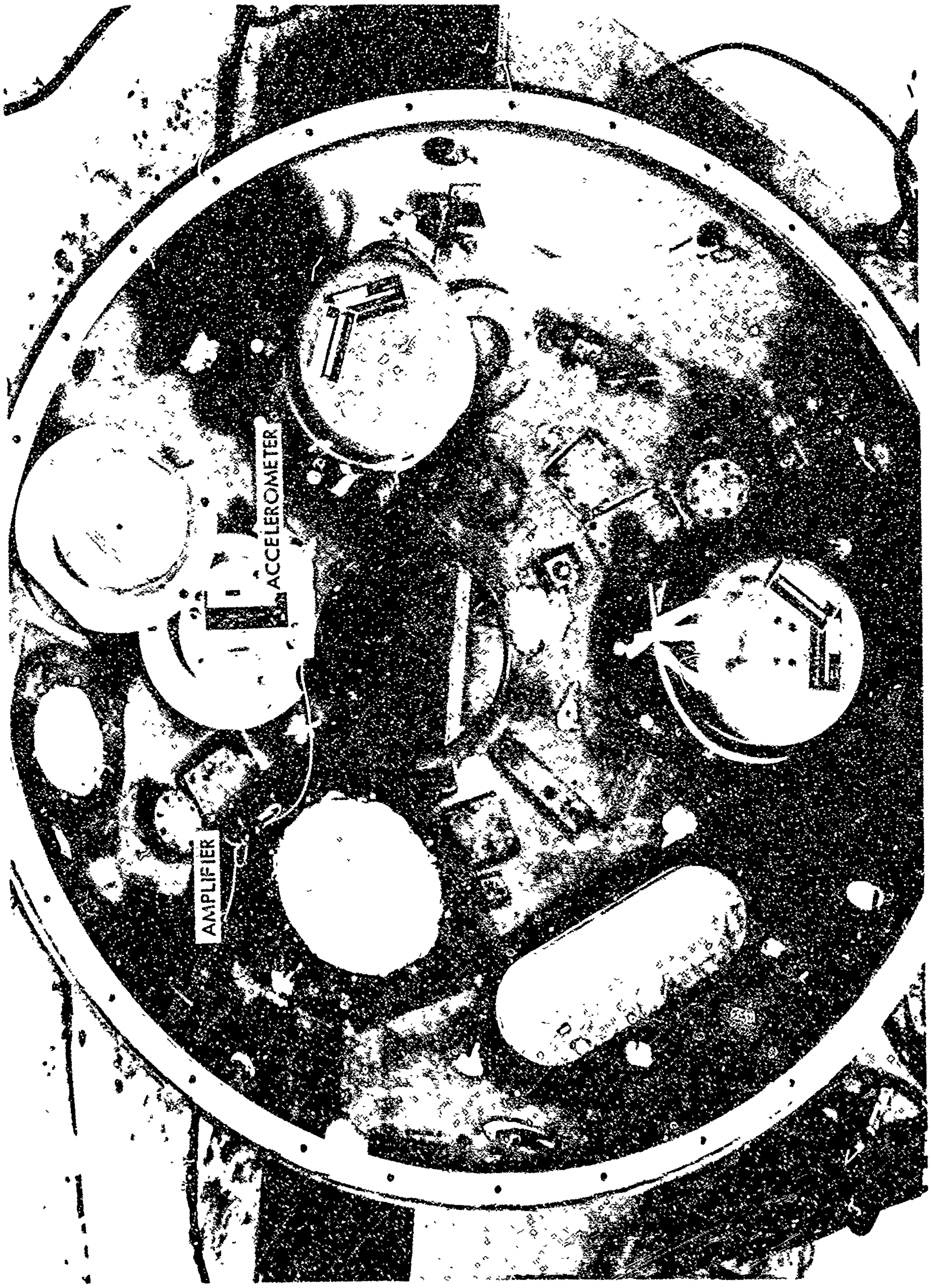

Figure 2. Interior View of Rear Cover Showing Accelerometer and Amplifier

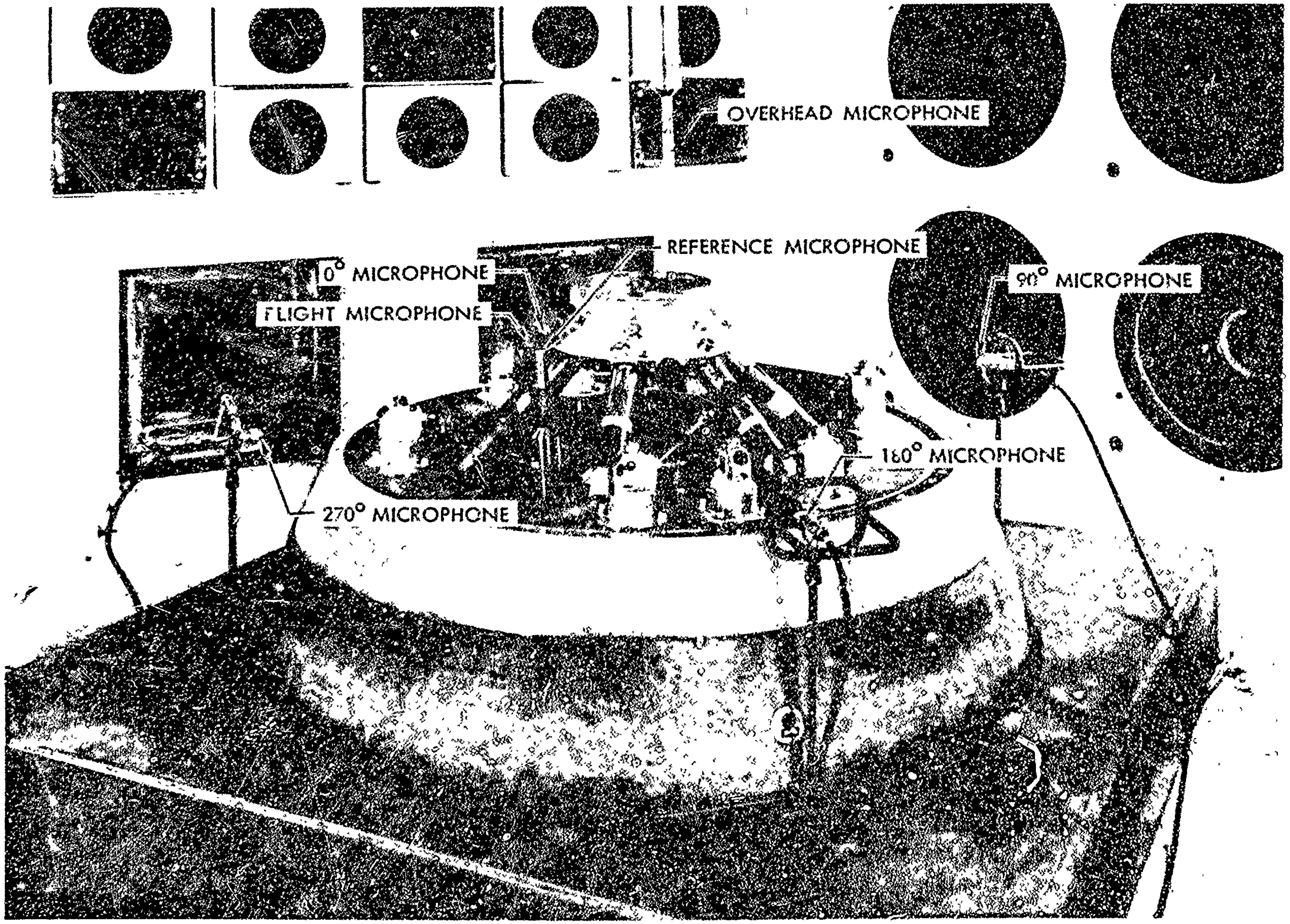

Figure 3. Location of Test Microphones (Test Specimen has Rear Cover Removed)

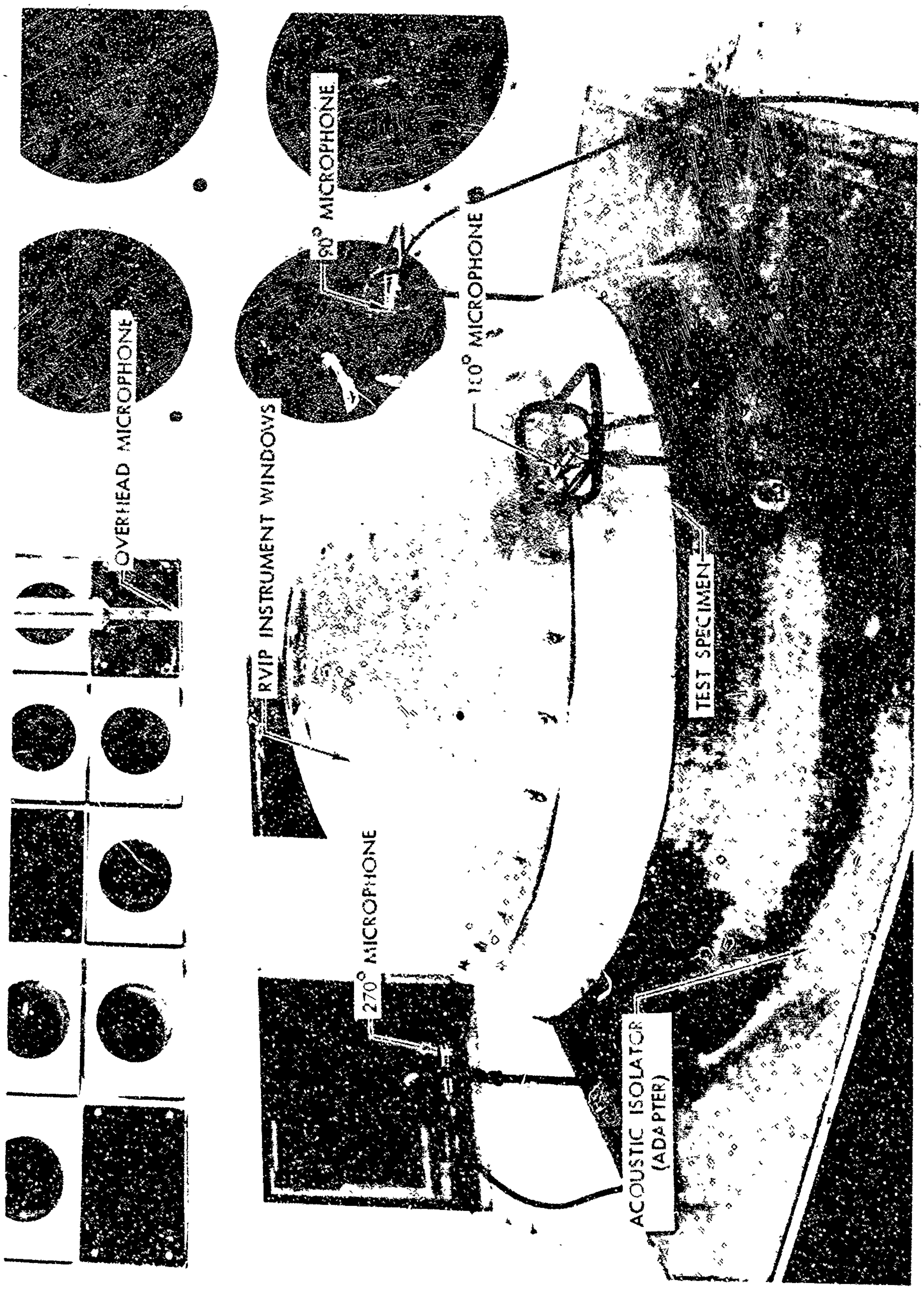

Figure 4. Acoustic Ground Test With Specimen in Reverberant Chamber

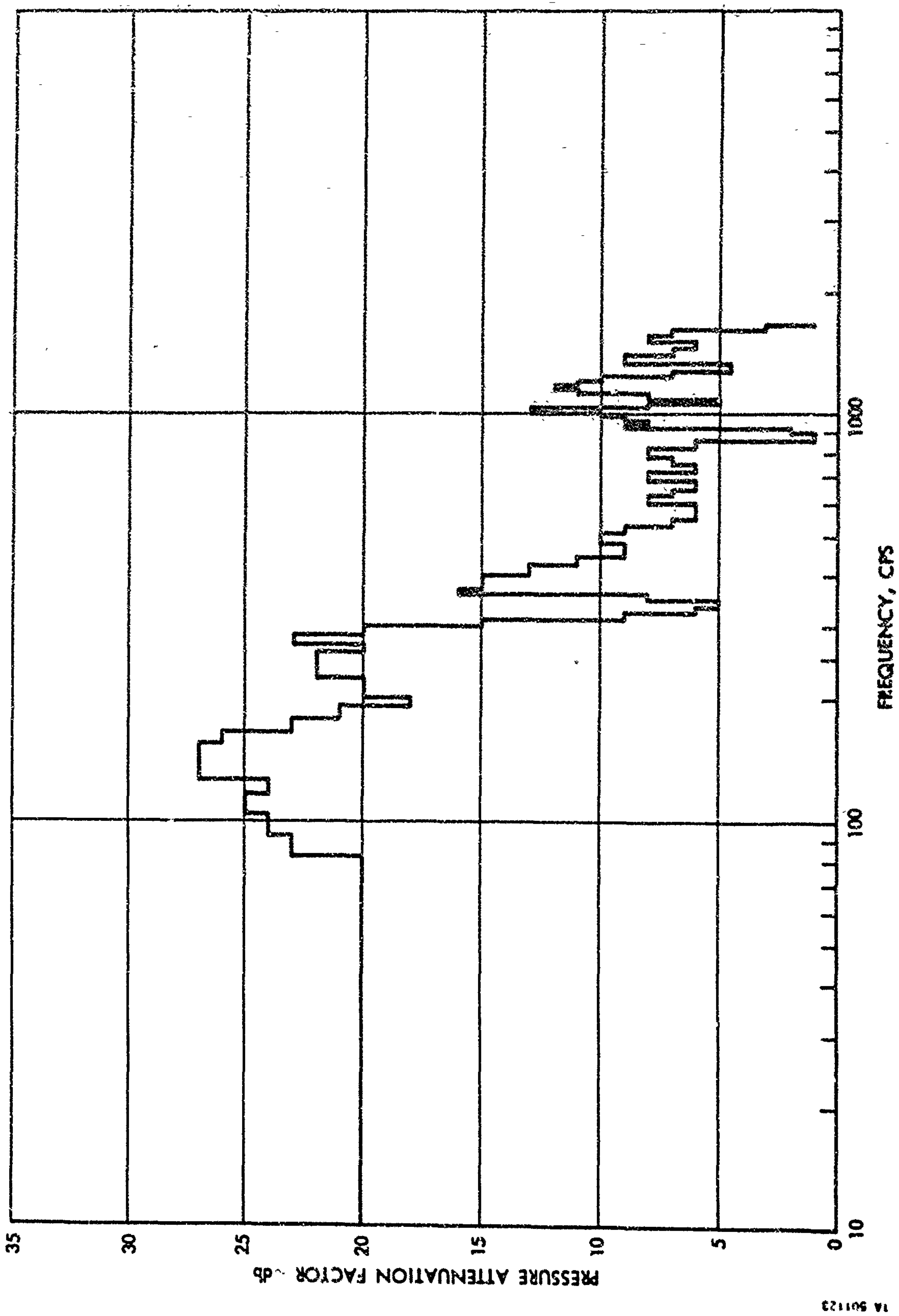

Figure 5. Pressure Attenuation Versus Frequency

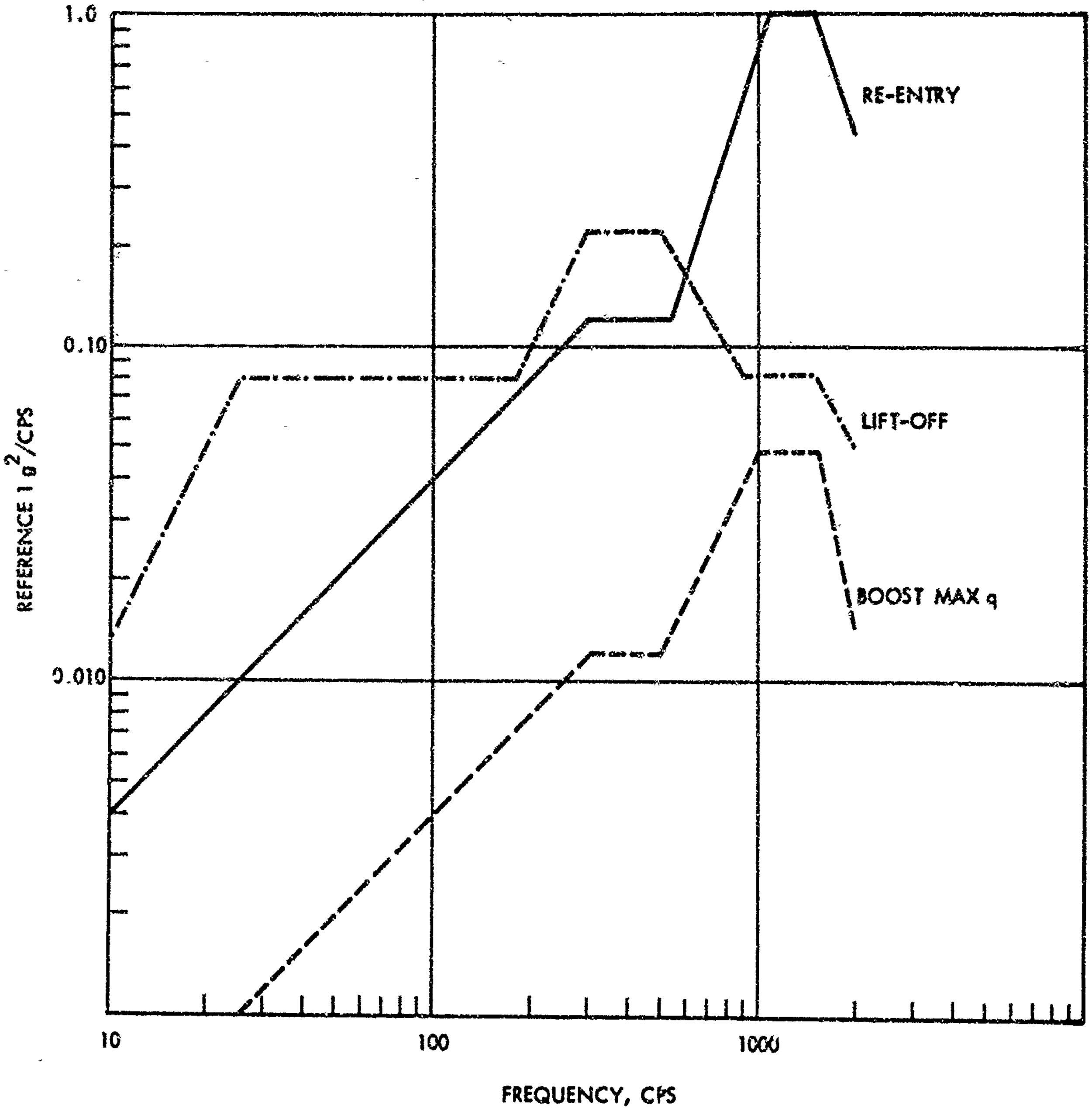

Figure 6. Comparison of Measured Flight Data, Presented as Normalized Acceleration Spectral Densities

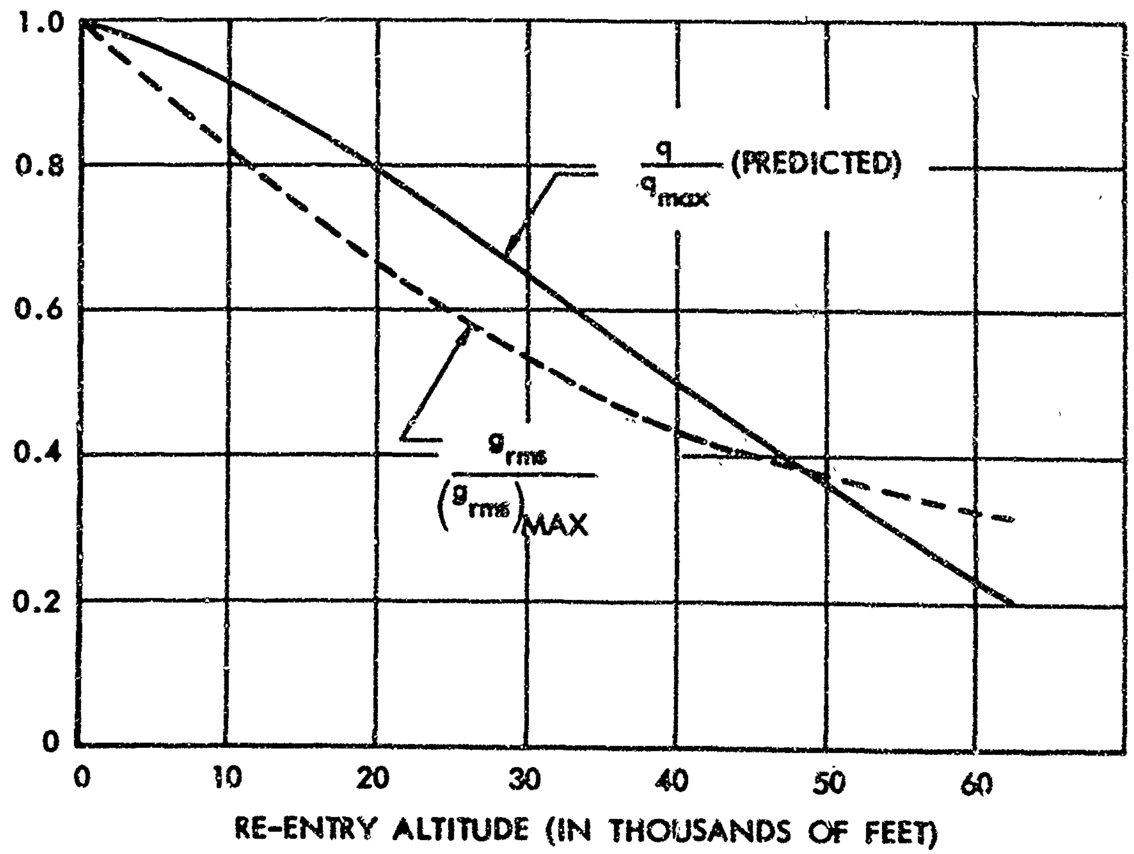

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Figure 7. Comparison of Normalized Predicted Dynamic Pressures and Measured Vibration Levels

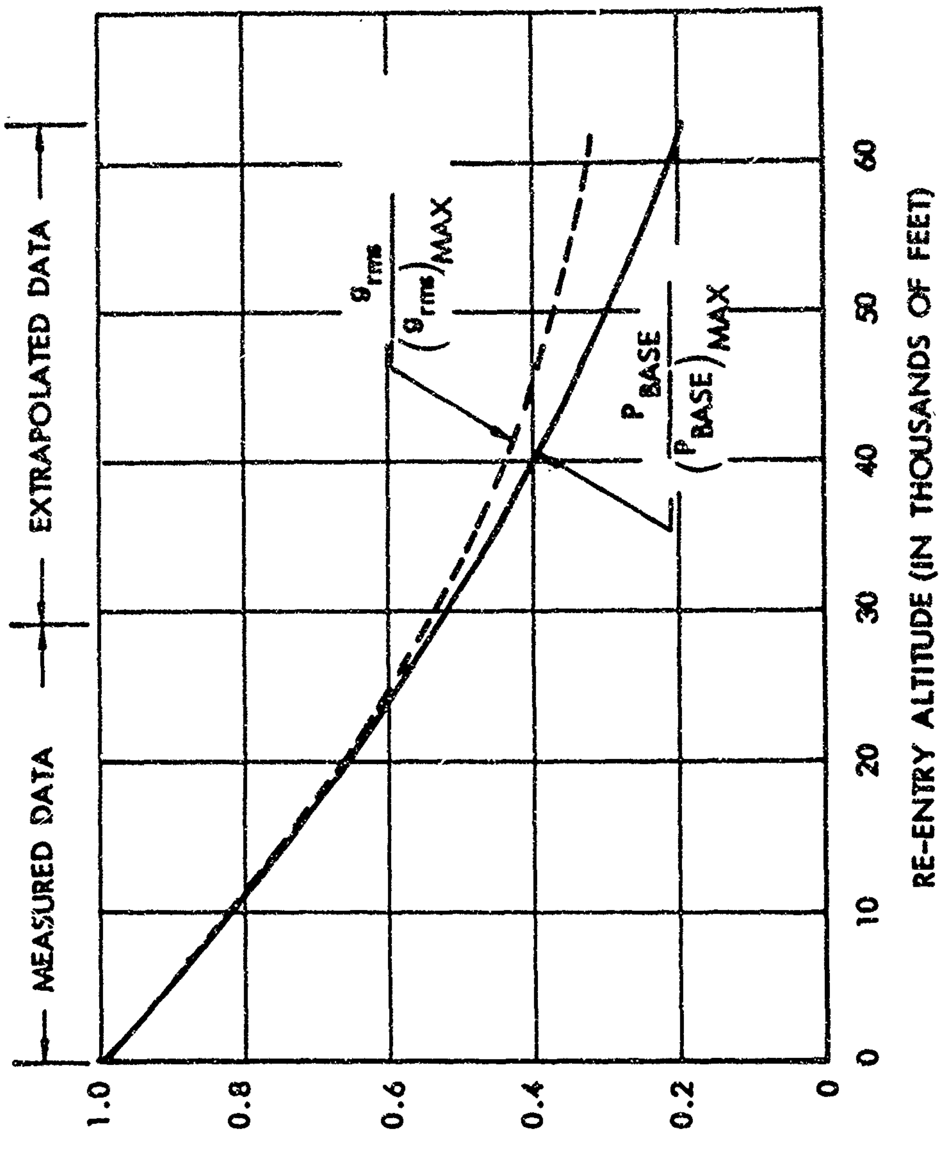

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Figure 8. Comparison of Normalized Vibration and External Base Pressure Measured During Flight

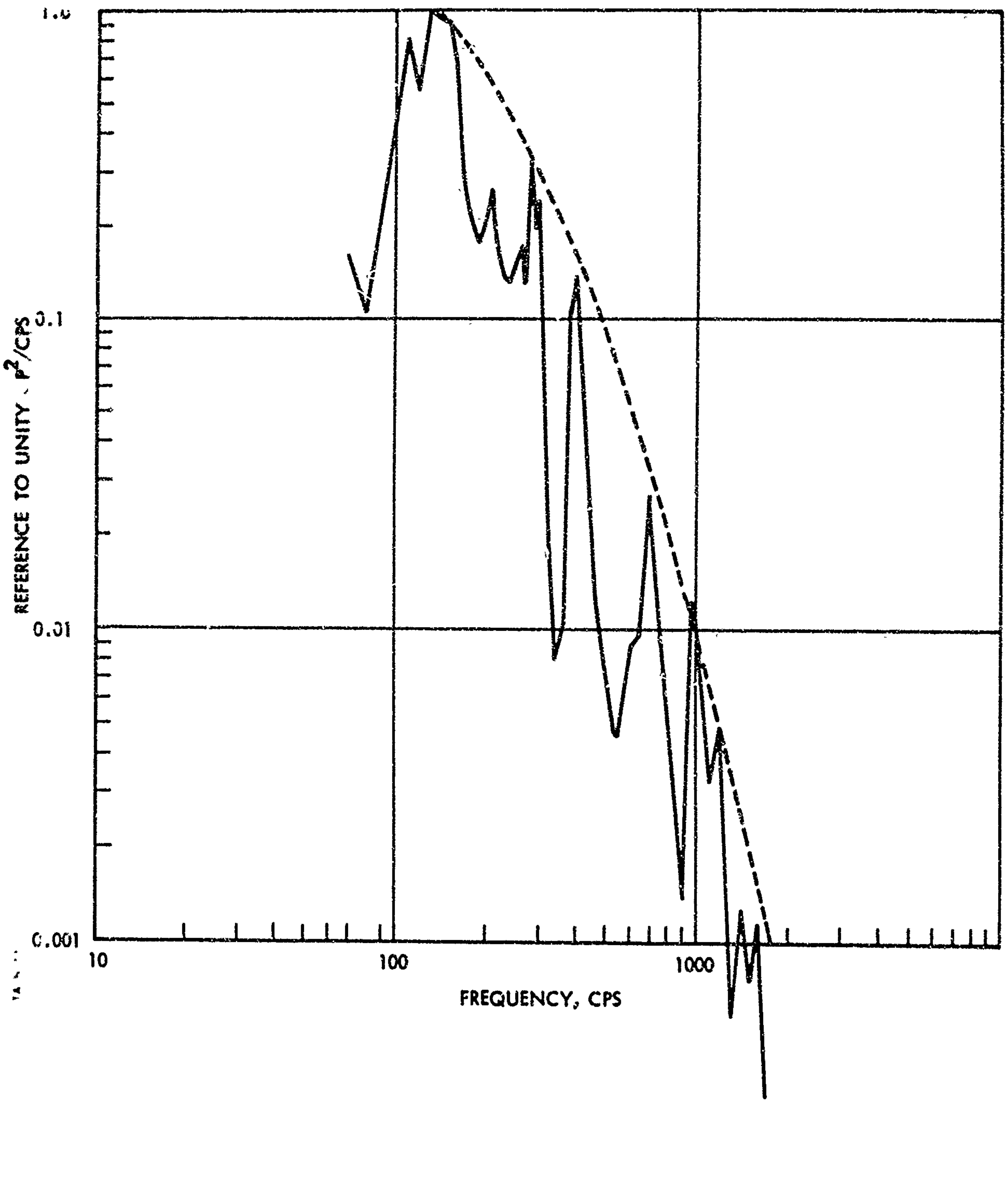

Figure 9. External Pressure Spectral Density Inferred from Internal Measurement

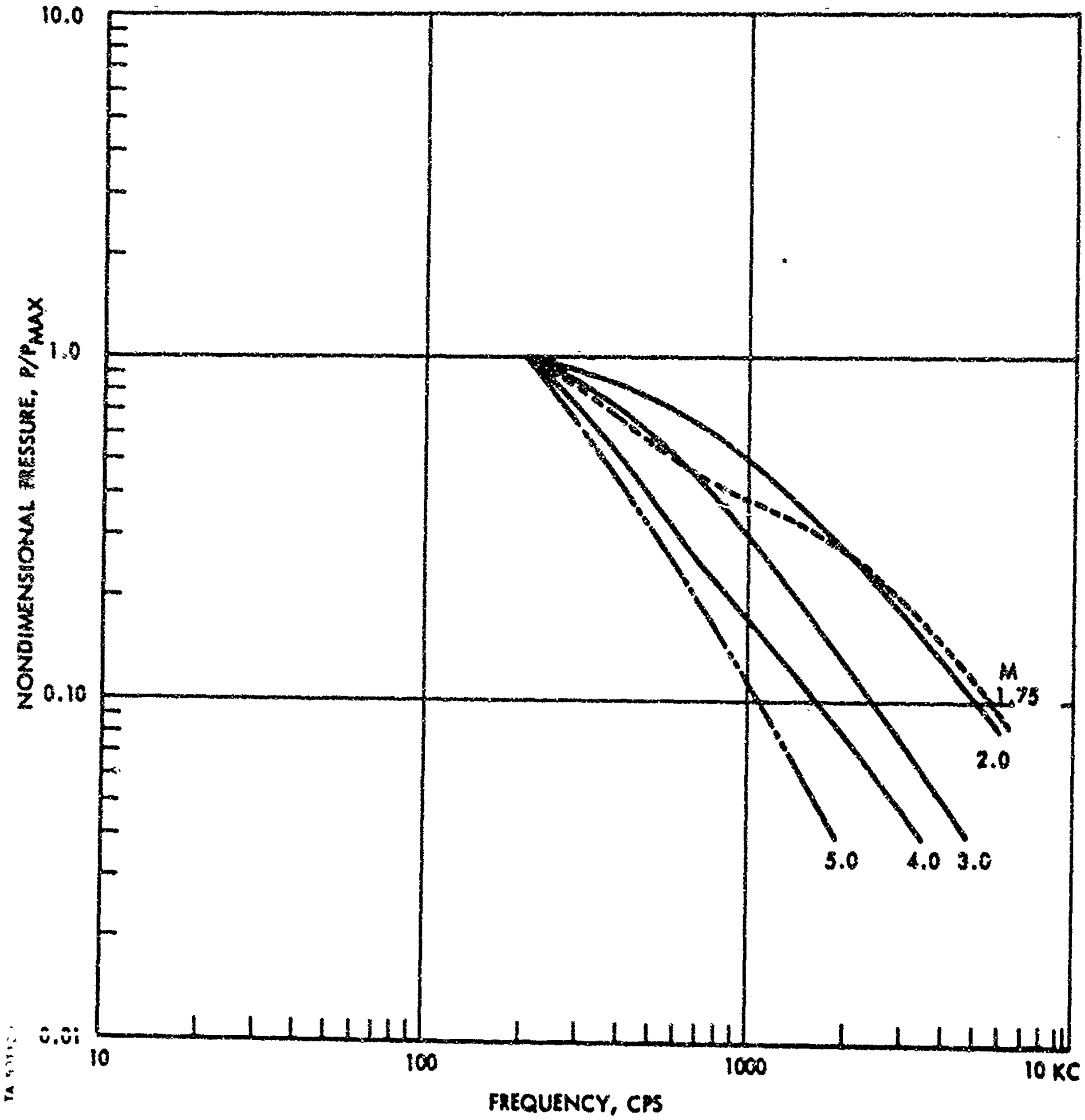

Figure 10. Boundary Layer Noise Spectra (Reproduced From Reference 6)

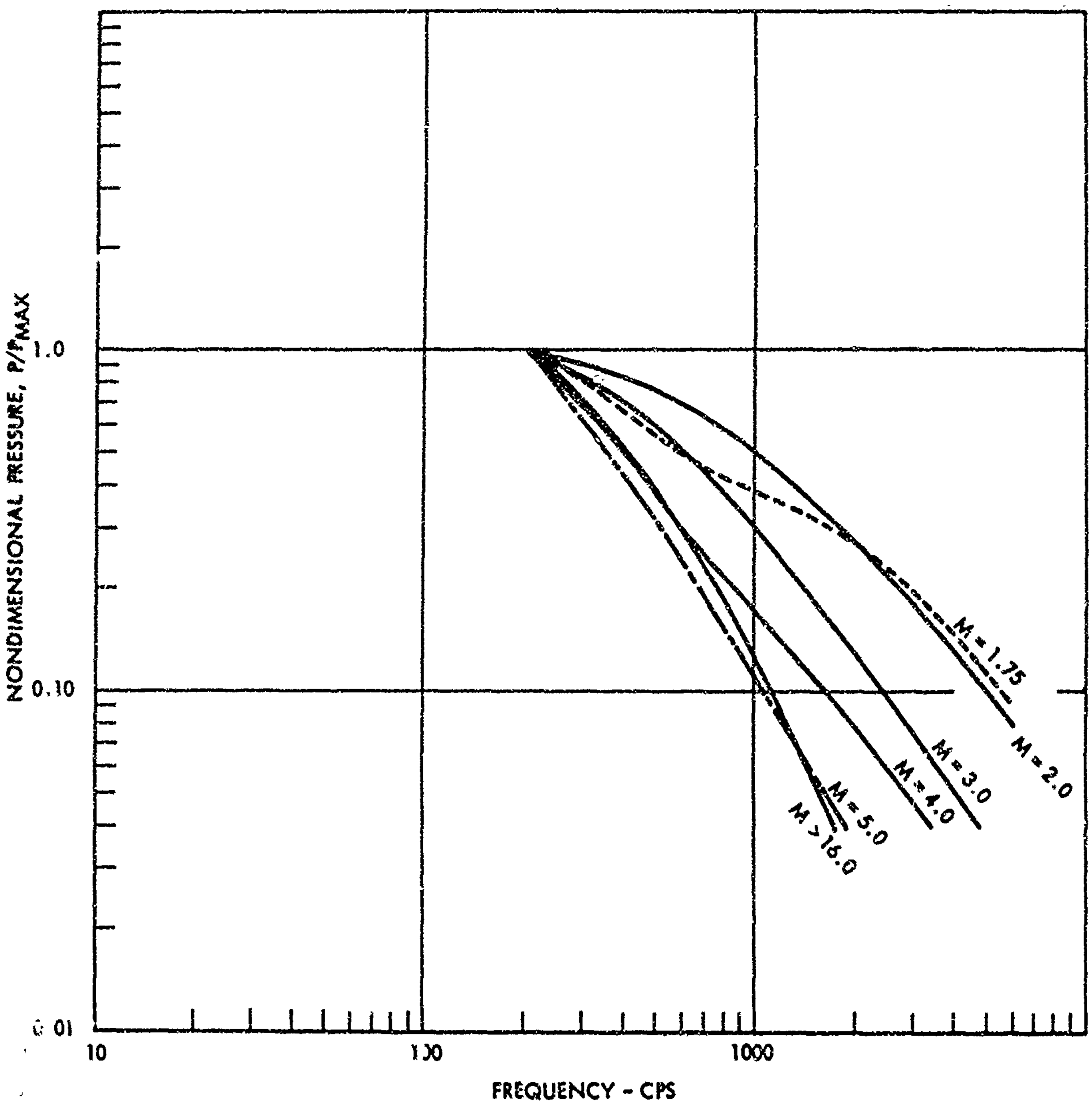

Figure 11. Comparison of Boundary Layer Noise Spectra

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KEY WORDS

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low frequency telemetry channels
boundary layer noise
structural vibration
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